A Ground-Based 2-Micron DIAL System to Profile Tropospheric CO_2 and Aerosol Distributions for Atmospheric Studies

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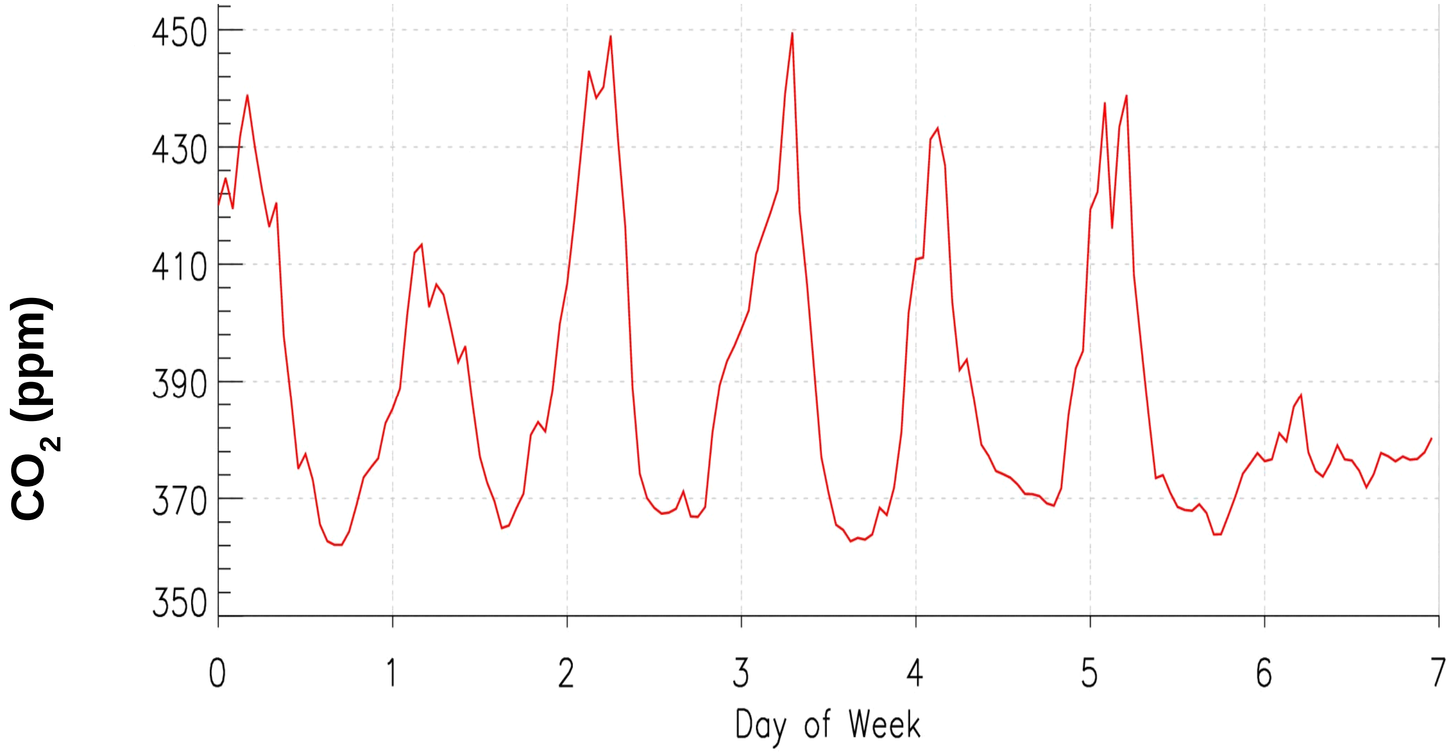
Objectives

- Technology development for profiling atmospheric CO_2
- Coverage over 0-5 km altitude range with 0.5% precision
- Deployable system for field studies, and as an anchor and validation tool for total column retrievals from the Orbiting Carbon Observatory (OCO)

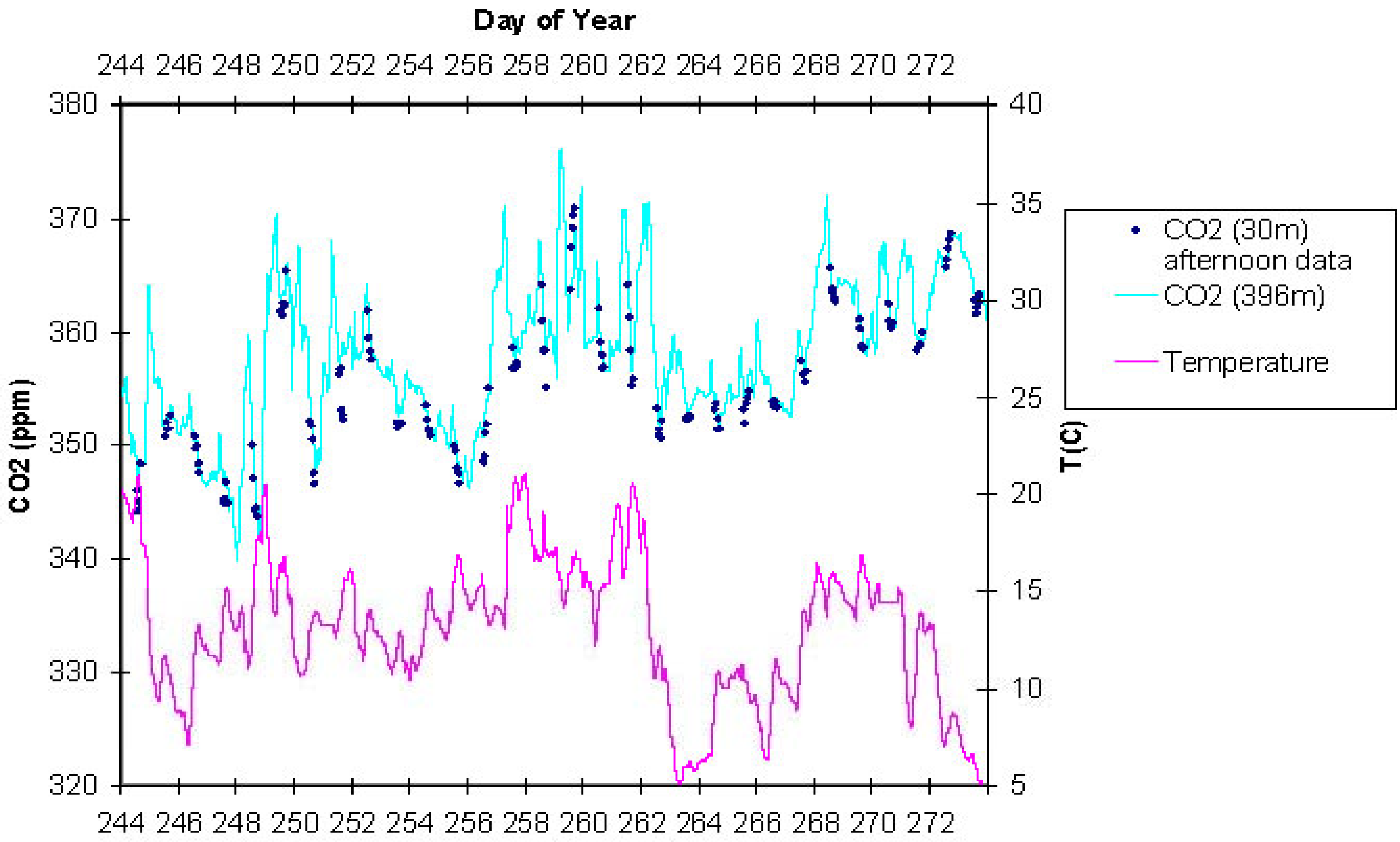
Need for Profiling of CO_2



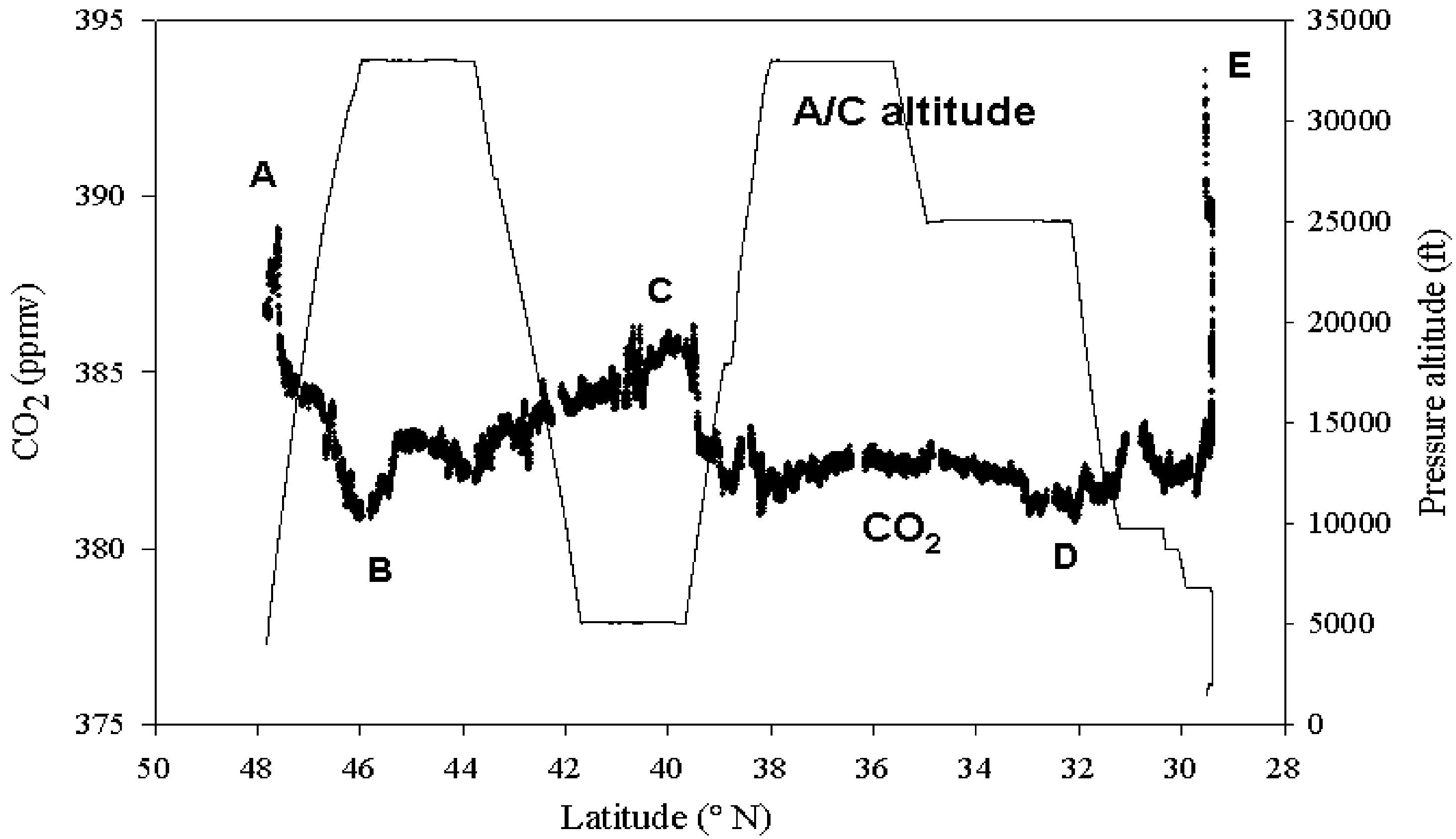
Diurnal variations of CO_2 using a NASA GSFC in situ LI-6262 sensor during the week of May 30, 2004. (Amelia Colarco, 2006)

Sources and sinks of CO_2 are located near the surface; and CO_2 is redistributed by passage of weather fronts, convection, dynamics, and transport

ABL CO_2 variations and their relation to synoptic weather

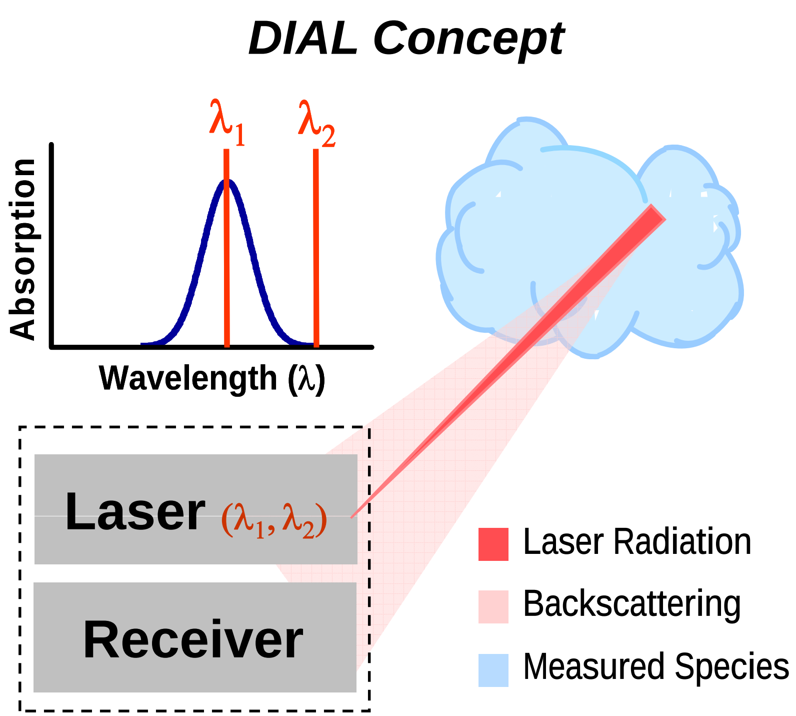


Advantage of CO_2 DIAL Profiling System



Variations in CO_2 observed along DC-8 flight track during INTEX-B using LI-6252 (Vay). Preliminary in situ data reveal A) BL to free trop transition, B) stratospheric air, C) biogenic and anthropogenic sources, D) tropical air, and E) free trop to BL transition.

Differential Absorption Lidar (DIAL) Technique and its Advantages



Advantages:

- **High vertical and horizontal resolution**
- **DIAL data permit direct inversion and absolute concentration measurements**
- **Simultaneous species and aerosol profiles, and cloud distributions**
- **Day and night coverage and no dependence on external radiation**

DIAL technique for Atmospheric CO_2 measurements requires suitable absorption lines; narrow-band, tunable, and line locked lasers; high efficiency and low noise detectors

Features

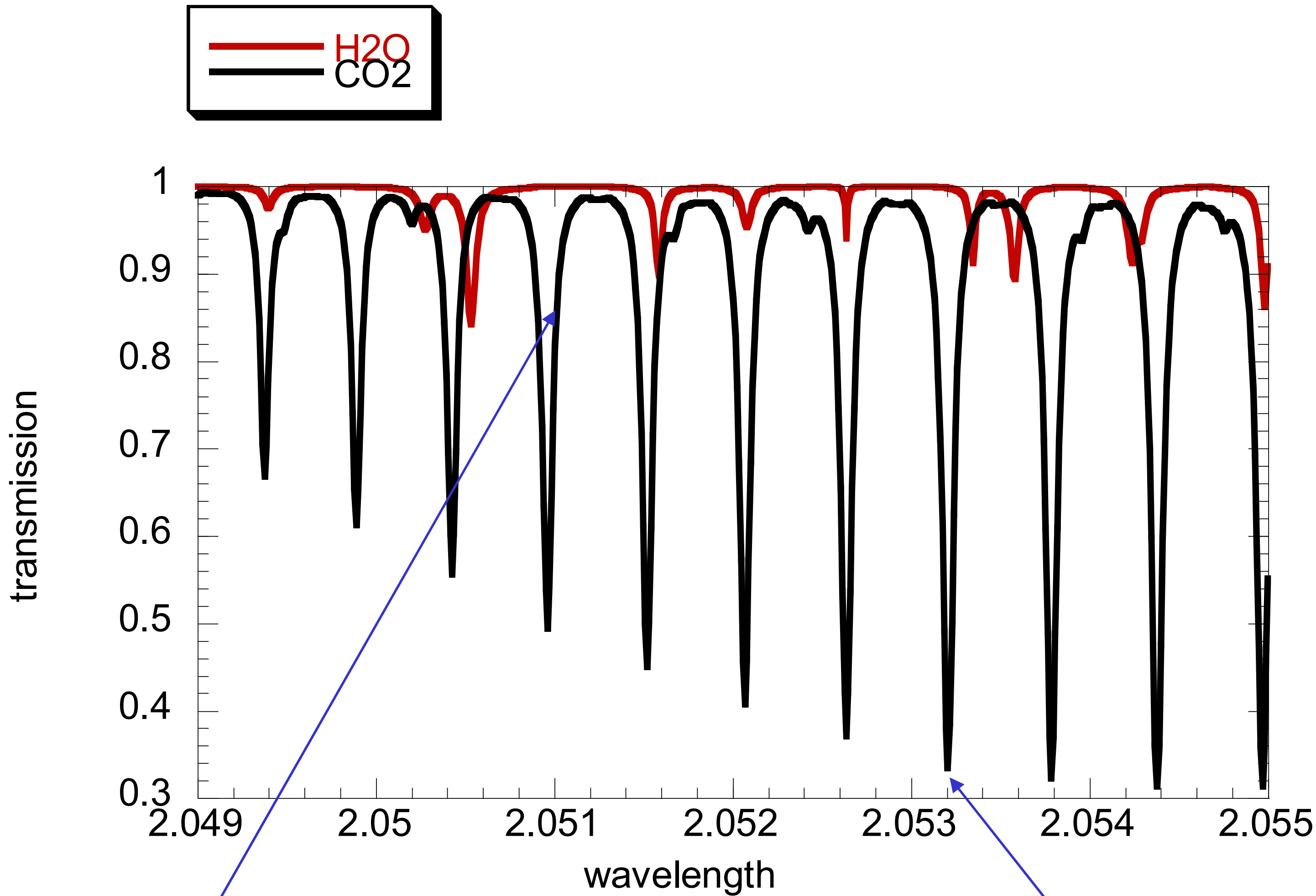
- Excellent CO_2 absorption lines at 2.05 microns
- State-of-the-art 2-mμ pulsed lasers
- High QE, low noise, high gain detectors
- Large collection area receiver

CO_2 absorption line selection and criteria

Select line that (i) allows optimum sampling of low troposphere, (ii) with low temperature sensitivity for differential absorption cross-section measurements, and (iii) has minimum interference from other species (in this case H_2O)

CO_2 lines in 2-micron region are very strong and require side-line operation. This requires line locking that will be off-set from line center.

Wavelength Selection

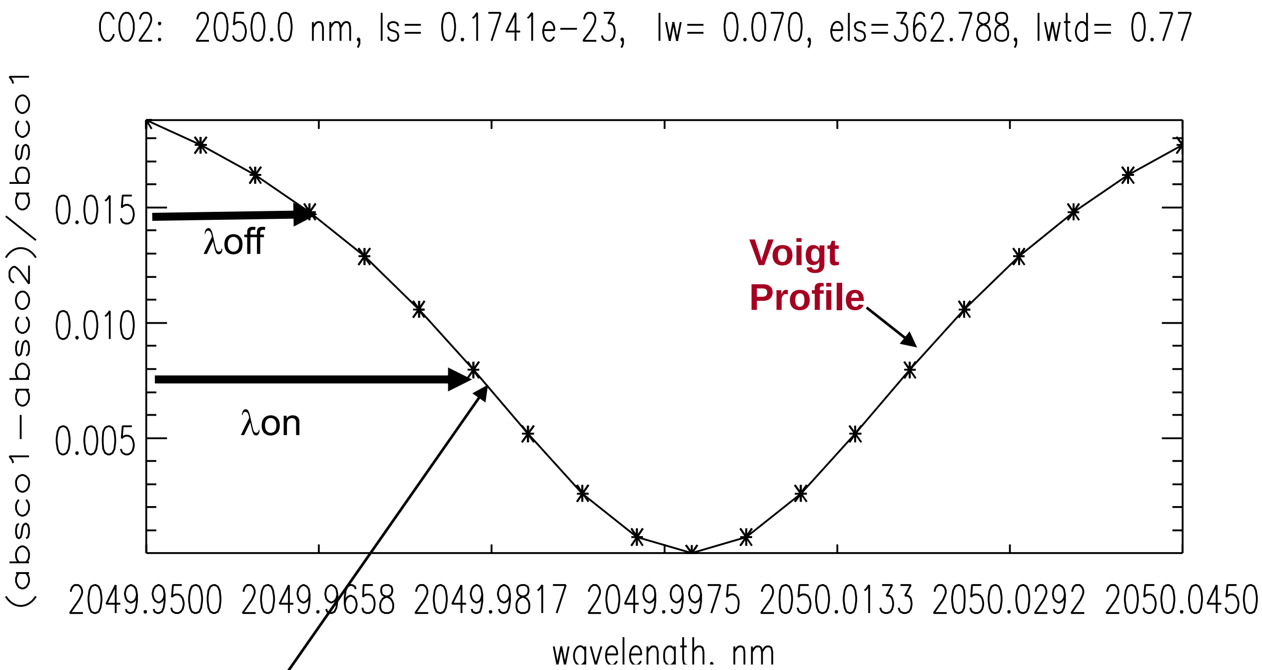


2050.967 nm: better in strength and temperature insensitivity. Moving to this line and operate on 'side-line'.

2053.204 nm: line described in proposal

Temperature insensitive CO_2 line selection

The $\Delta\sigma/\Delta T$ for mixing ratio measurements of the selected line R30 at 2050.967 nm*

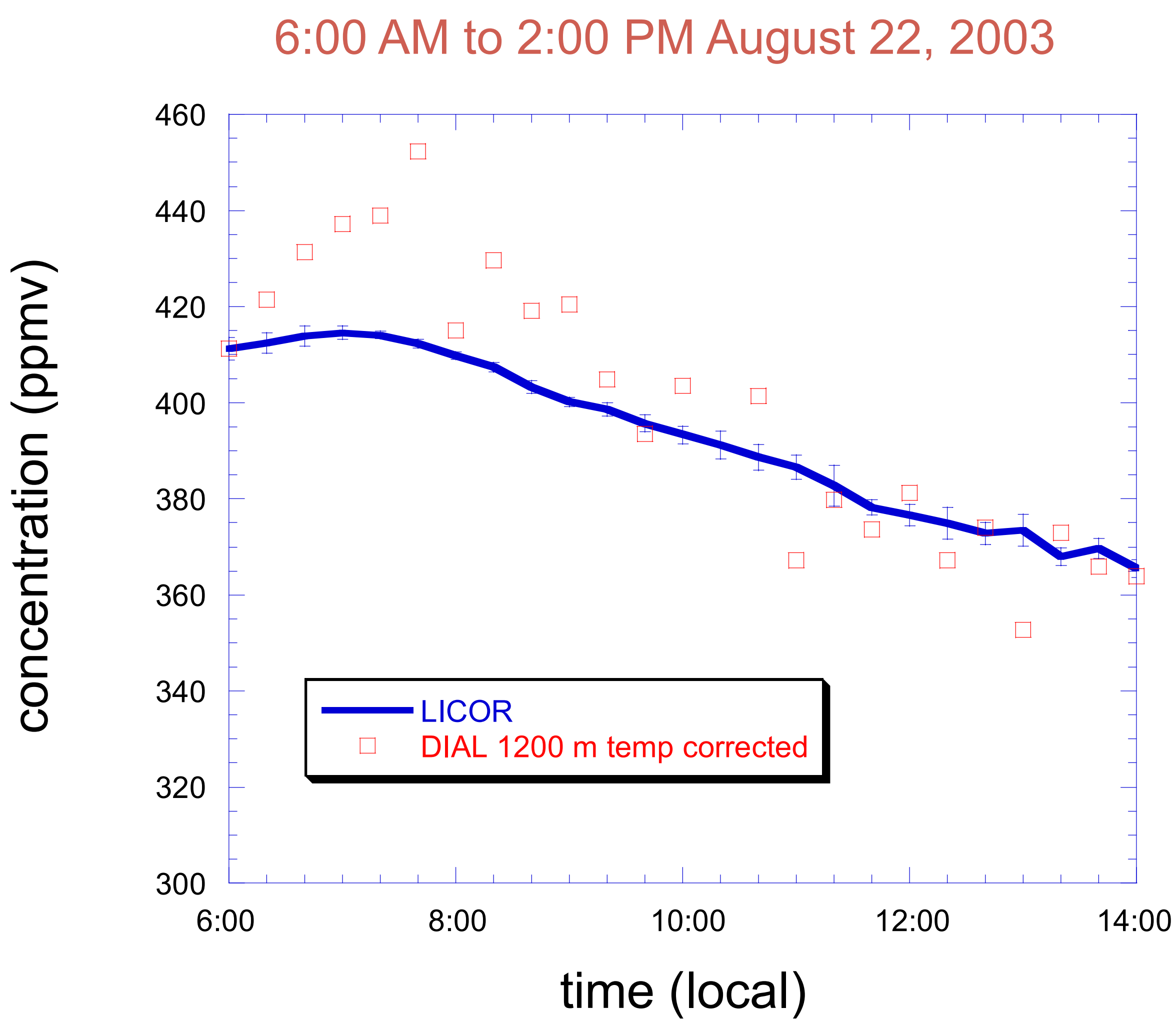


Sensitivity of absorption cross section σ to a change of 5 K temperature

Note: The $\Delta\sigma/\Delta T$ is very small ~0.14%/K, and even that is reduced by the off-line

***A nominal wavelength was used in the temperature sensitivity calculations, and it has no impact on the results that are presented**

Heritage: CO_2 concentration measured by DIAL Heterodyne detection using a 4" diameter telecope



1-2% 1σ standard deviation over column lengths

DIAL taken over a column
From 0 to 1200 m.

In situ sensor was a LI-COR
Model 6252, with inlet
Mounted 7.5-m high.

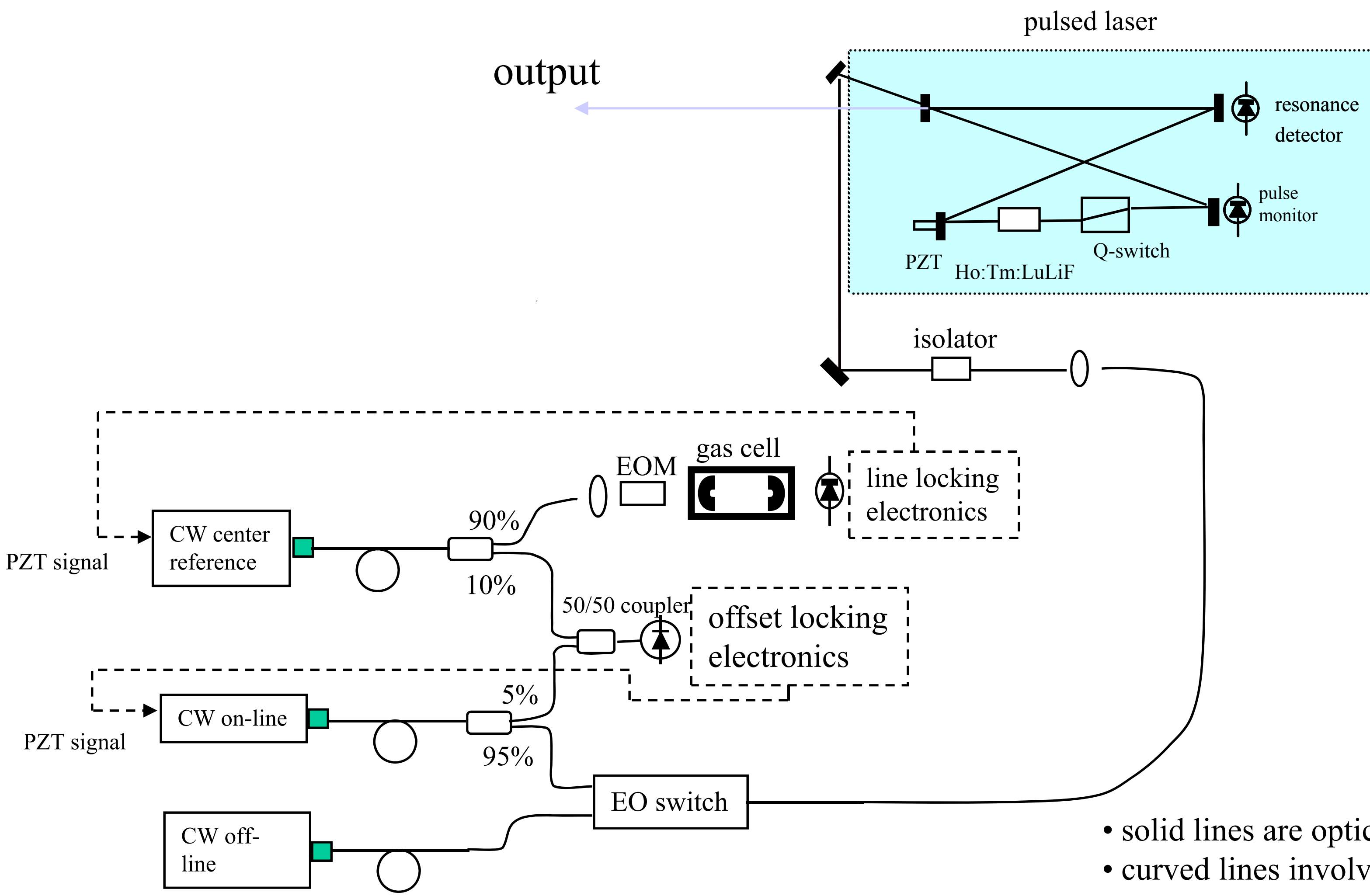
LI-COR was at 100-m range
from DIAL.

Grady et al., 2004

Laser Developments under earlier NASA Programs Including LRRP

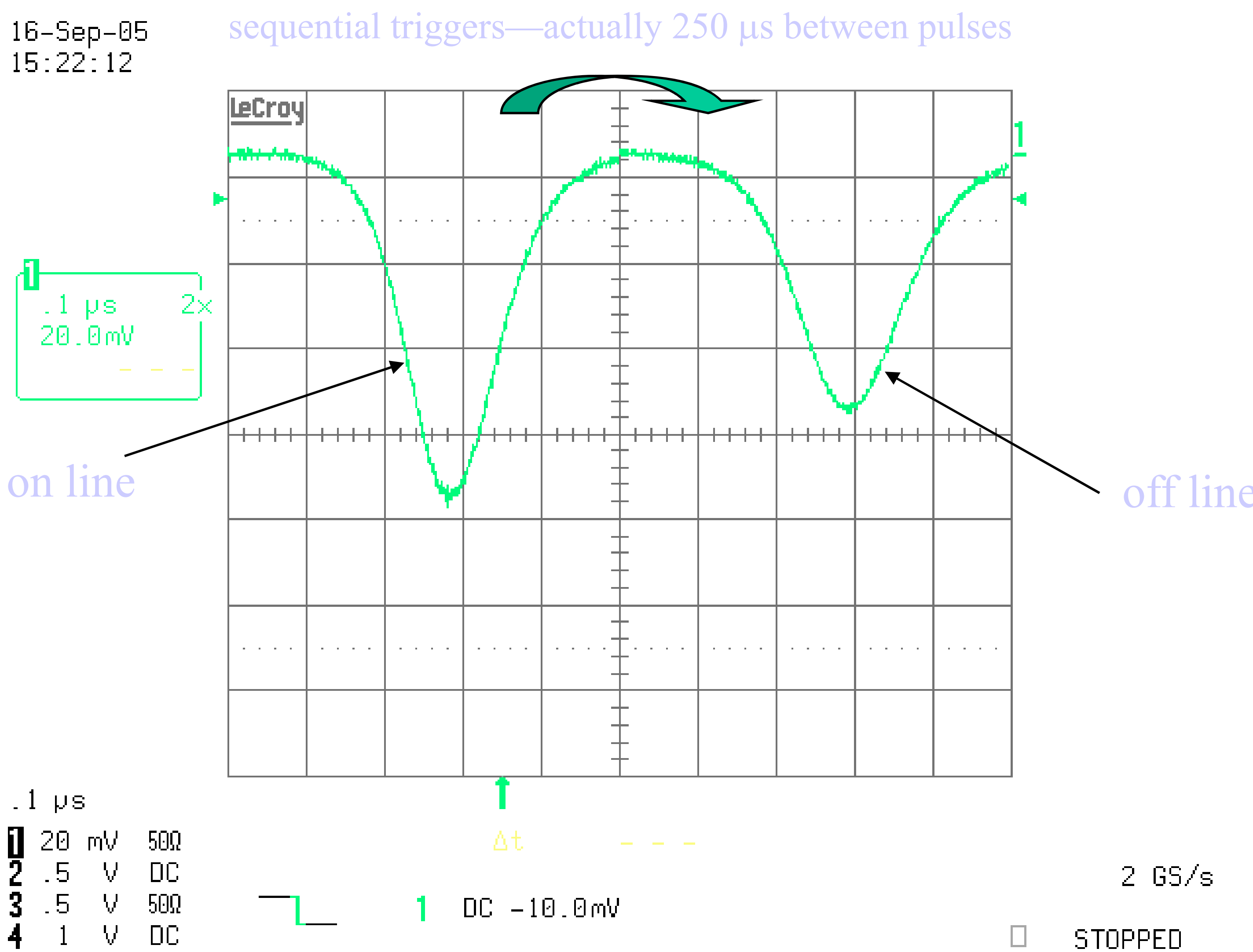
•Pulsed laser for range resolved profiling
•Double pulsed operation to sample the same air mass by on- and off-laser pulses
•Wavelength stability and spectrally narrow output
•Line-locking with respect to a selected CO_2 line
•Operation on a side of the line for optimum absorption cross-section selection

Transmitter System Architecture

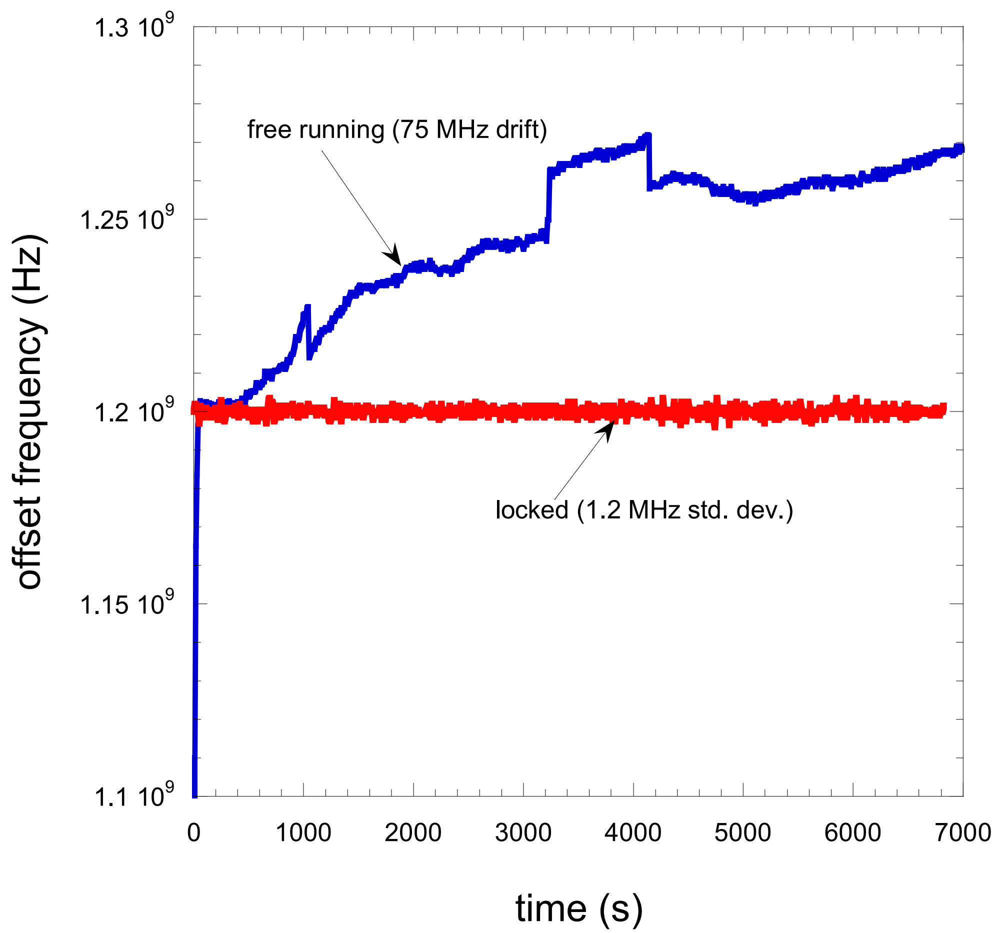


- solid lines are optical paths
- curved lines involve optical fiber
- dashed lines are electronic paths

Double-Pulse Wavelength-Switched Results



Side Line Offset Locking Characterization

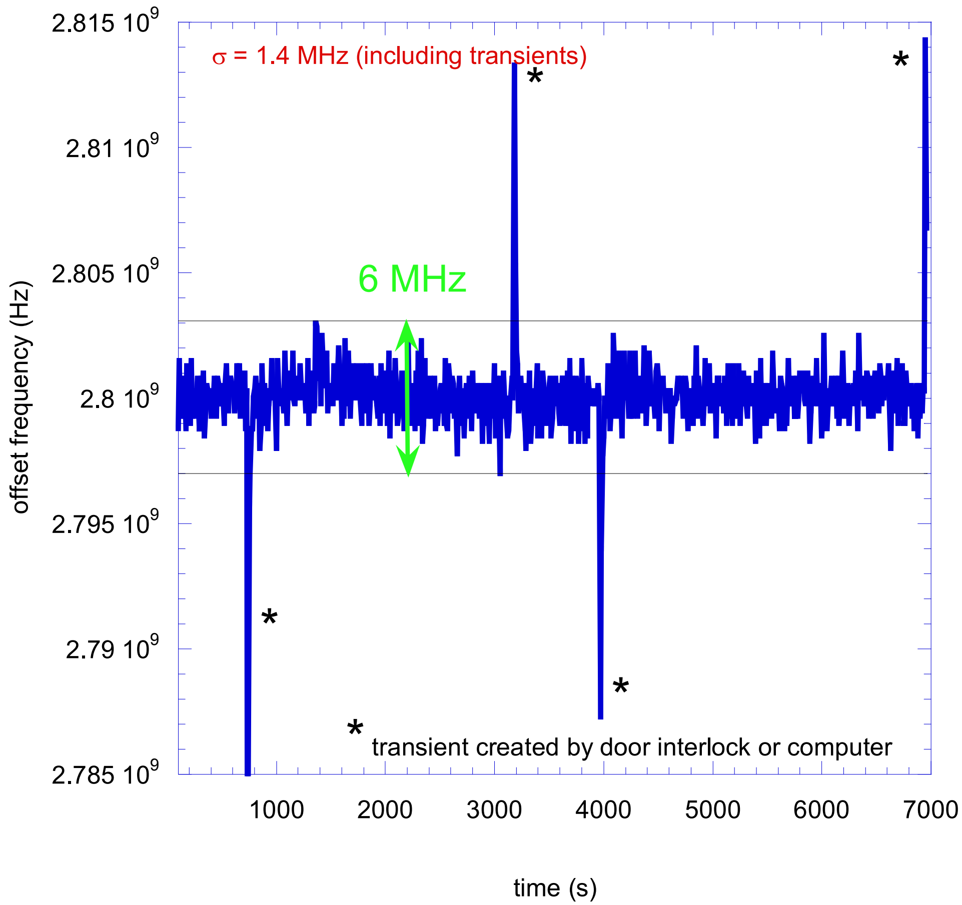


- Electronic control holds an offset from center-line locked laser.

- Offset can be electronically programmed.

- Test here assesses quality of offset lock set for 1.2 GHz (37.3 pm).

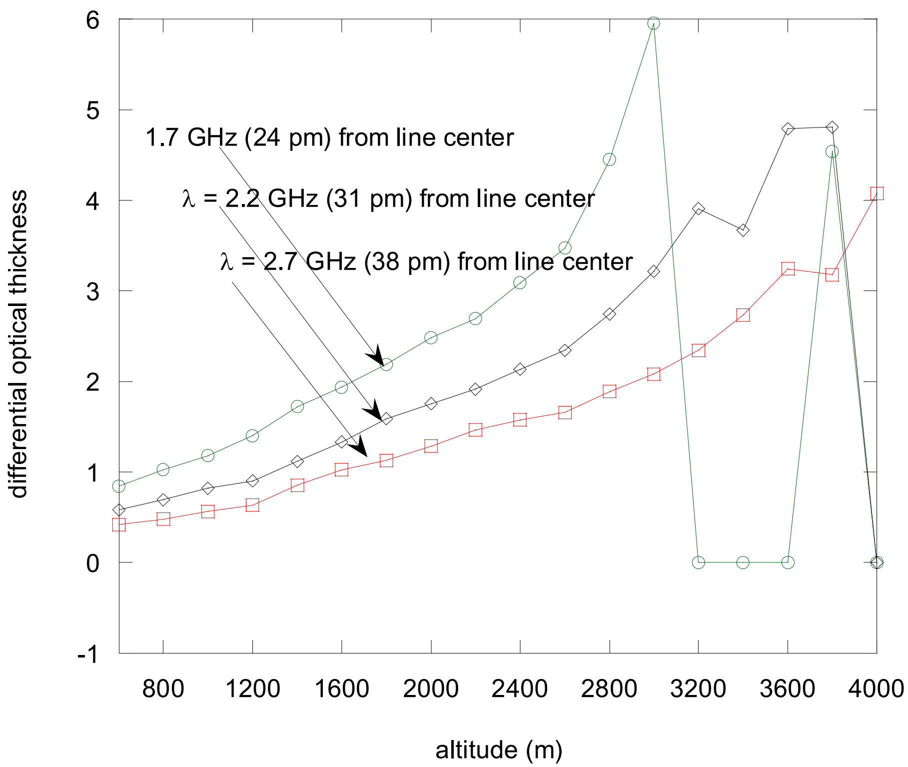
Side Line Offset Locking Characterization



- Electronic control holds an offset from center-line locked laser.
- Offset can be electronically programmed.
- Test here assesses quality of offset lock set for 2.8 GHz (37.3 pm).

Atmospheric test: changing side-line tuning, continued

diff. opt. thick. = $\ln (S_{off}/S_{on})$



- beam vertically pointing
- processed on 200-m range bins.
- 2000 pulse pairs.
- three sets of data
- optical depth changes with wavelength, demonstrating the usefulness of this technique.

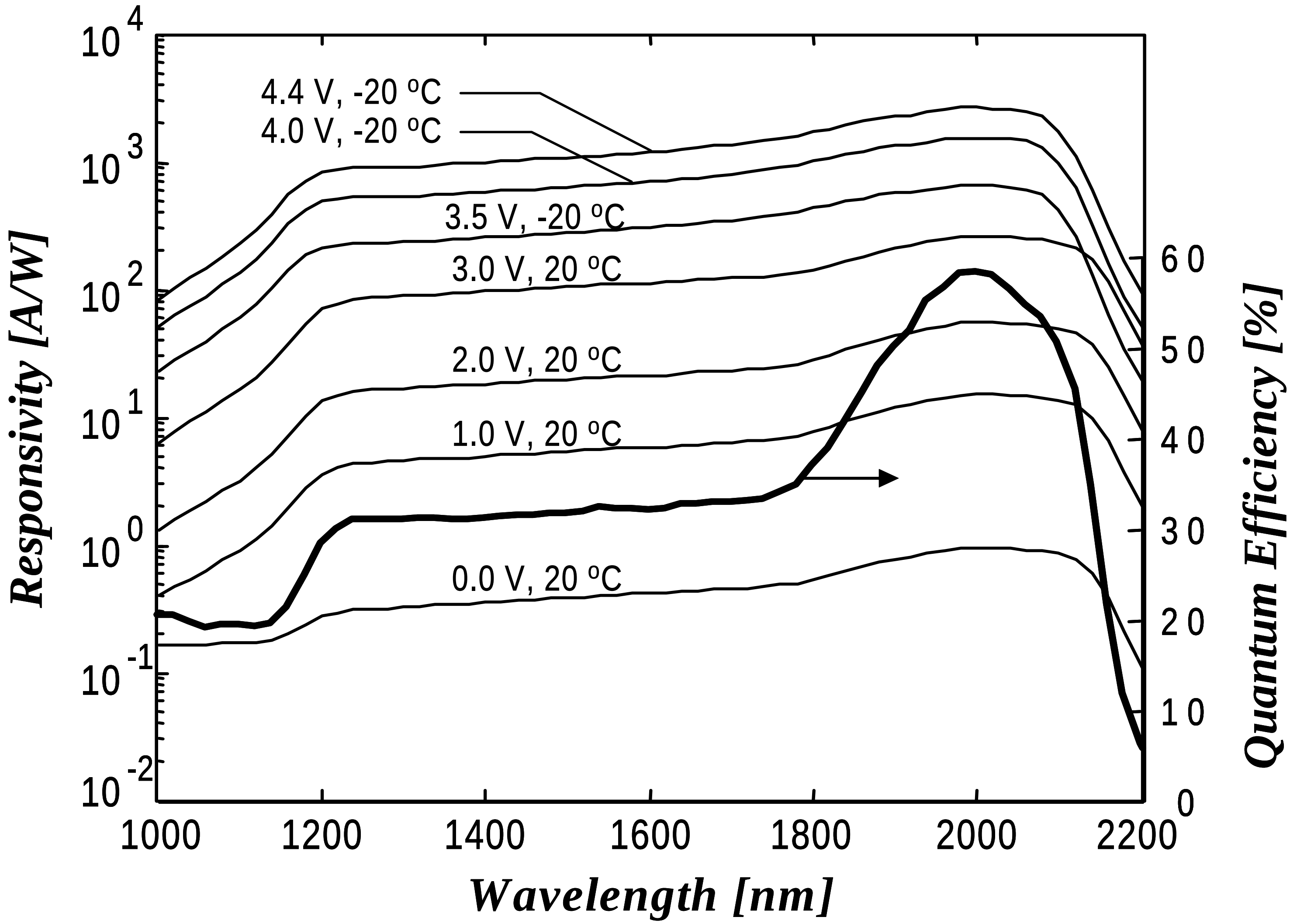
CO_2 DIAL (IIP) Goals/Requirement for detector

Advanced Detectors development needed that exceeds the performances of the commercially available detectors

- Responsivity @ 2.00-μm $\geq$ 50 A/W
- Operating temperature, T ~ - 20 C
- Low noise (NEP $\leq$ 2 to 5×10^{-14} W/$\sqrt{\text{Hz}}$) for far field
- Quantum Efficiency @ 2.00-μm $\geq$ 50%
- Bandwidth $\geq$ 5 MHz
- Collecting area diameter: 200 - 1000 μm

New AlGaAsSb/InGaAsSb phototransistors acquired and characterized at SED under LRRP—these showed high sensitivity at 2 micron wavelength.

AlGaAsSb/InGaAsSb Phototransistor With High Sensitivity at 2 μm



This detector has small (200 μ diameter) collection area

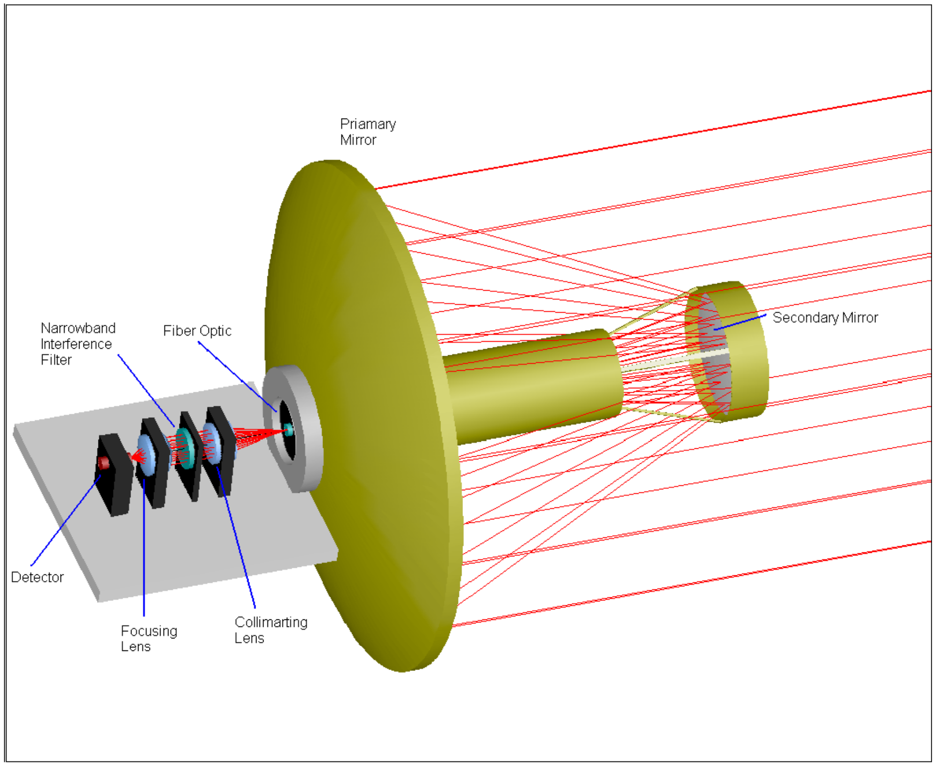
Design considerations of an optical receiver system

Features:

Large collection area (16” diameter) telescope

Small area detector (200 μm)

Full beam overlap at ~ 0.5 km



Considerations

Receiver FOV

Biaxial or co-axial

F# of telescope

Near and far field signals

Alignment stability

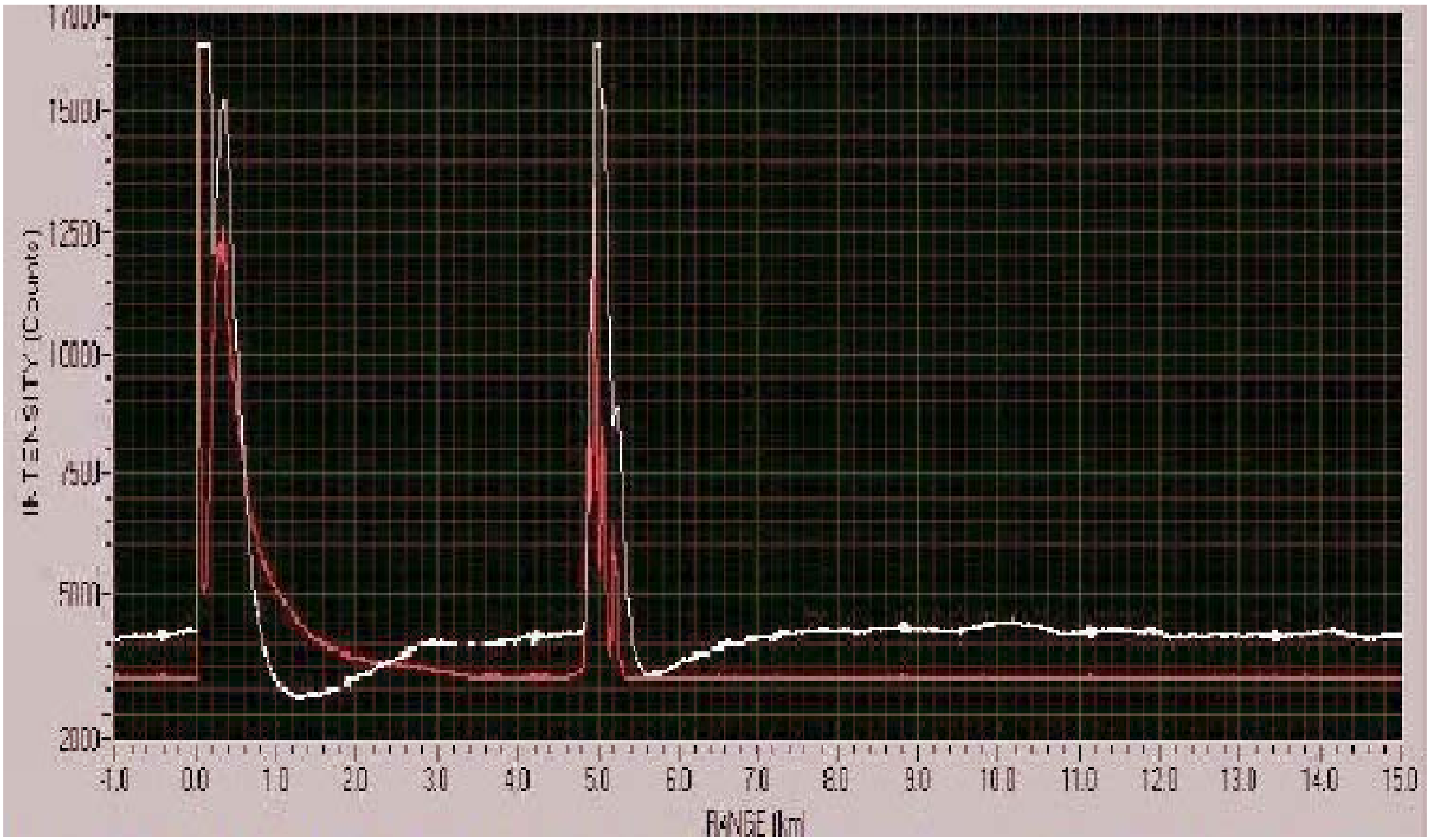
Atmospheric Tests of Phototransistors

- Atmospheric tests conducted at NCAR (June 5-9, 2006) to test the sensitivity of small area (200 μ) phototransistors.
- High sensitivity Aerosol Scanning Lidar (REAL) system of NCAR's at Boulder, CO was used for atmospheric testing of new detectors.
- REAL operates in the 1.5 micron region and the phototransistor has reduced sensitivity in this region

Date: June 8, 2006
Time: 16:22:09 GMT
File: pic6
Elevation: 90
Azimuth: 310

Detector: LPE A1-b10 Raw
Bias Voltage: 3.5V
Temperature: 20oC
TIA Gain: 1000Ω
Amp. Gain: 30dB

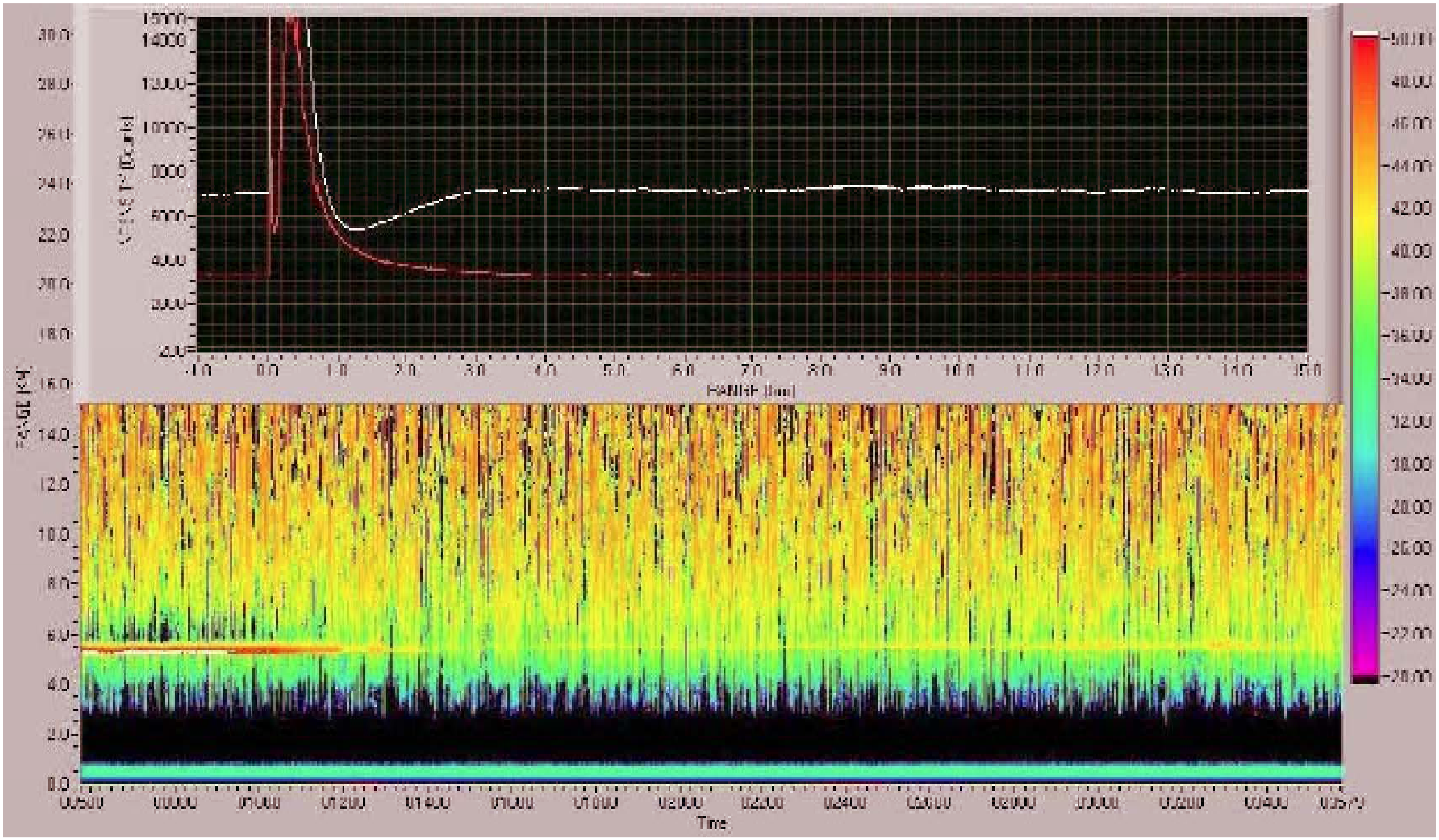
File: REAL.20060608_153255.bscan
Comments: Looking at thin cirrus cloud at 5 km. The cloud gets thinner. Even the boundary layer, at about 3 km, can be seen with the phototransistor.



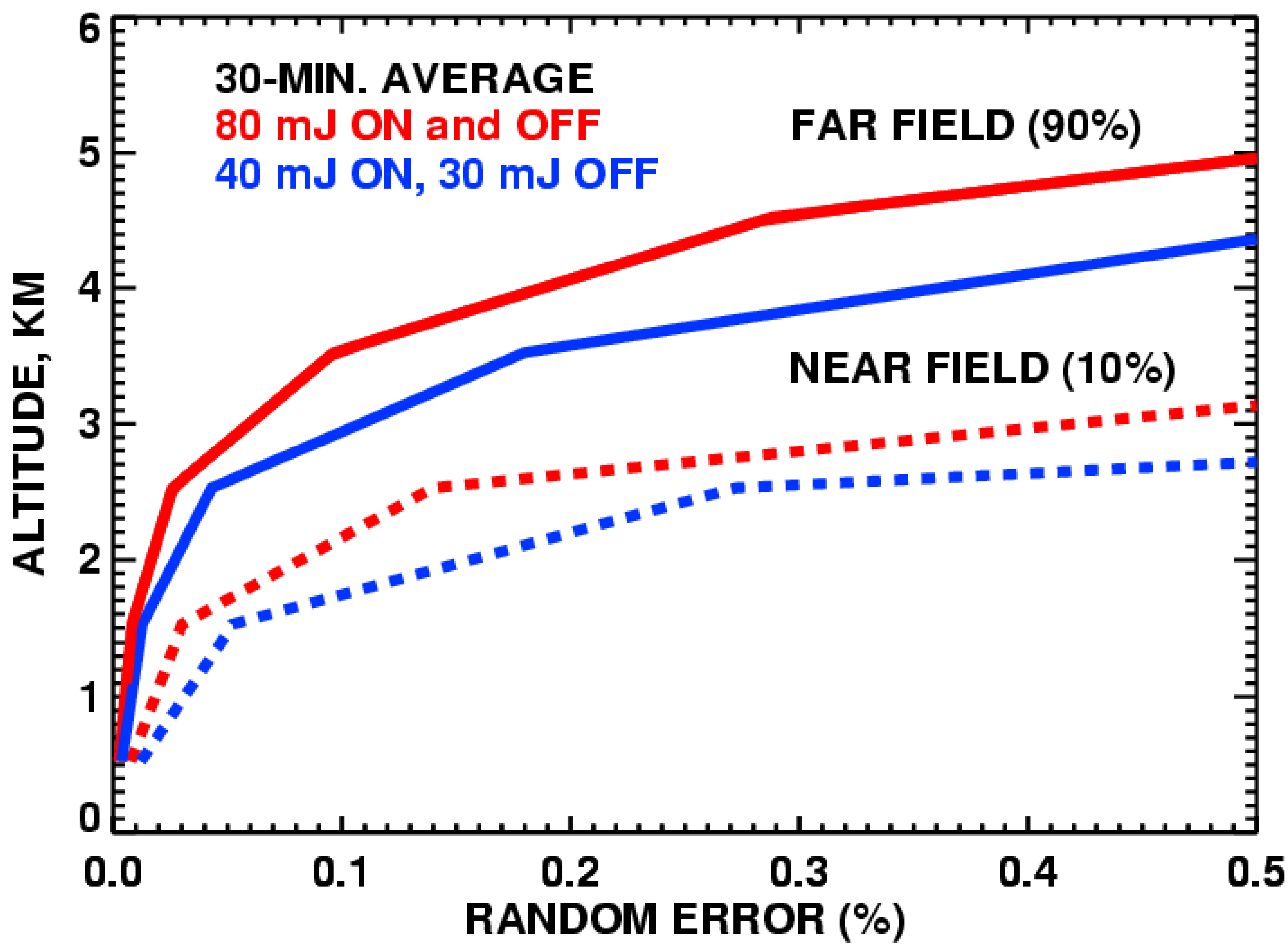
Date: June 8, 2006
Time: 16:40:44 GMT
File: pic10
Elevation: 90
Azimuth: 310

Detector: LPE A1-b10
Bias Voltage: 3.5V
Temperature: 10oC
TIA Gain: 1000Ω
Amp. Gain: 30dB

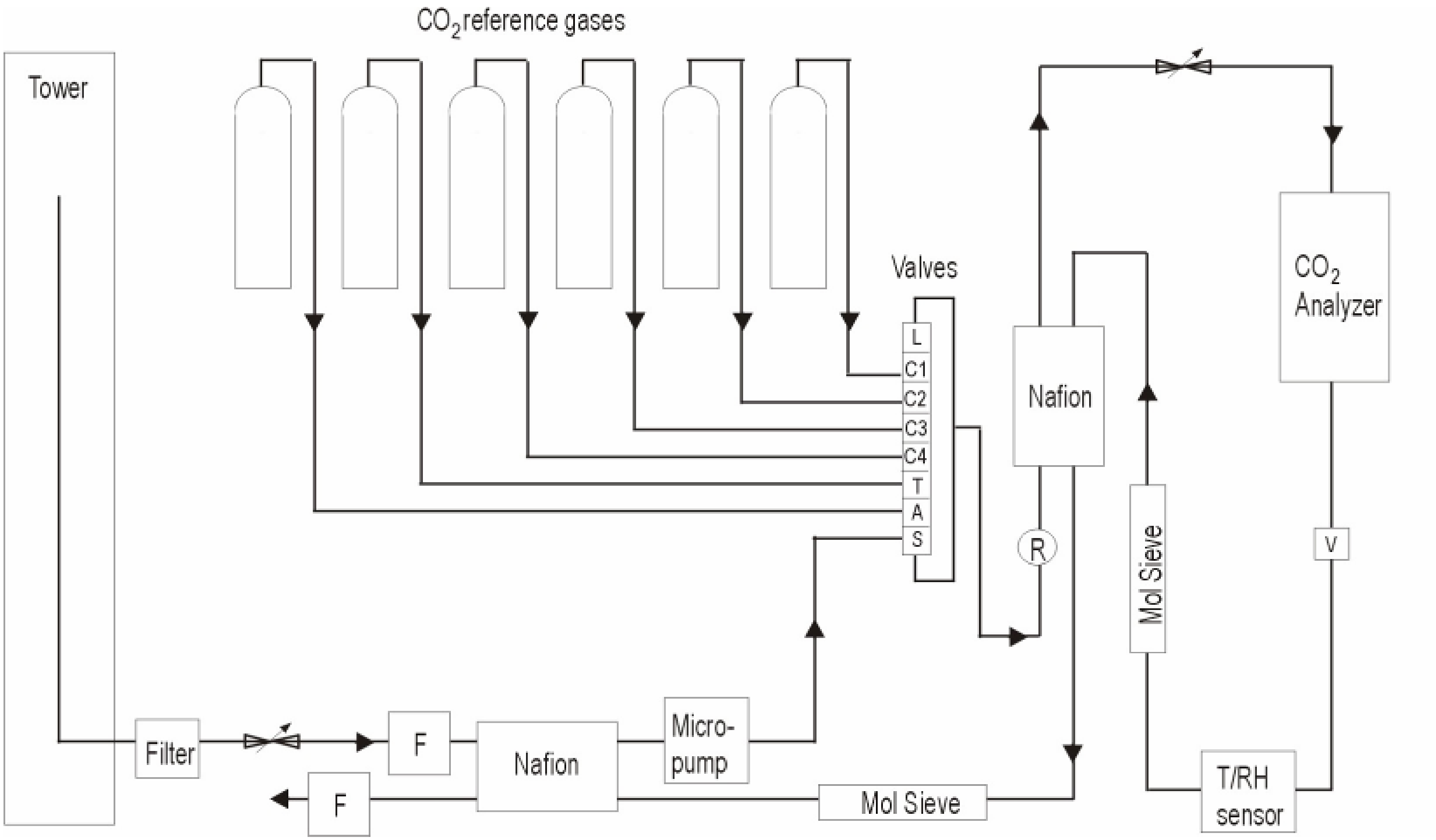
Raw File: REAL.20060608_162626.bscan
Comments: Cooling the phototransistor to 10°C
Although the feature becomes very weak (20% above bkgd.)
But still can be detected easily with the
phototransistor (SNR is about 1)



Projected performance of two channel system

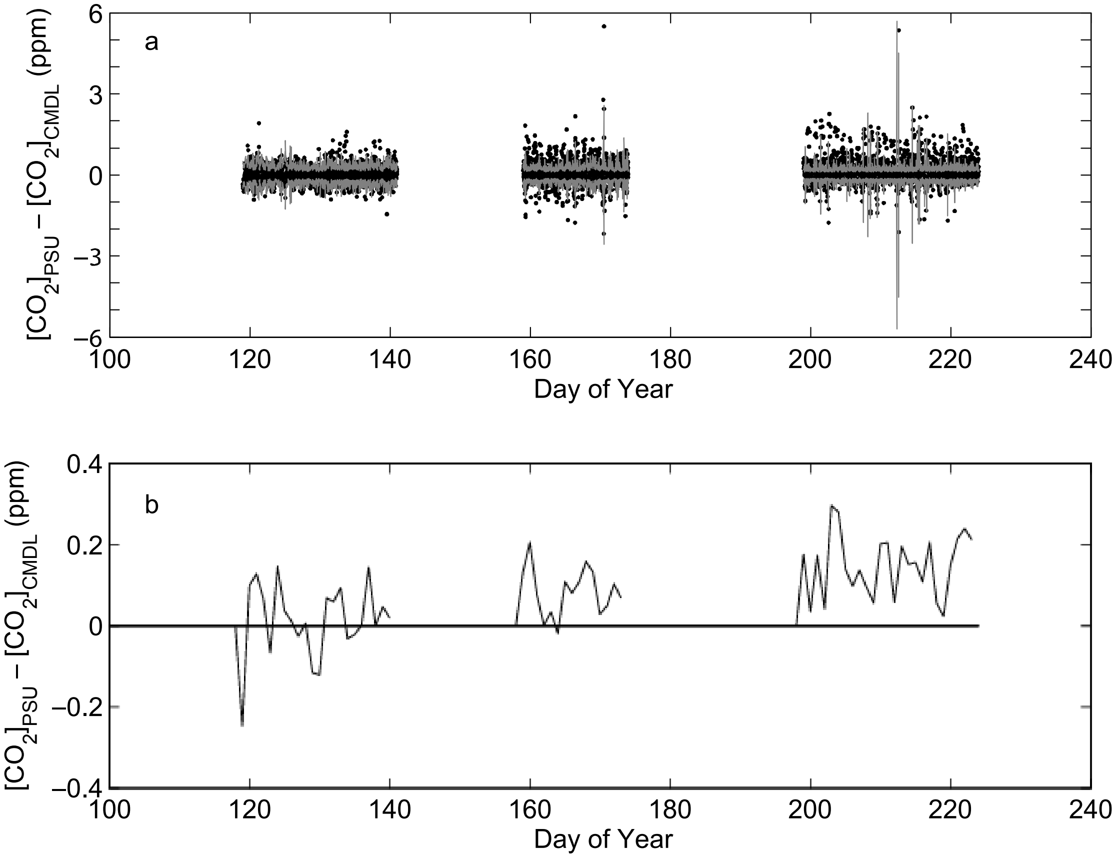


The PSU-NCAR CO_2 sensor design



For more information, see www.amerifluxco2.psu.edu

Performance Testing



Difference of daily averages

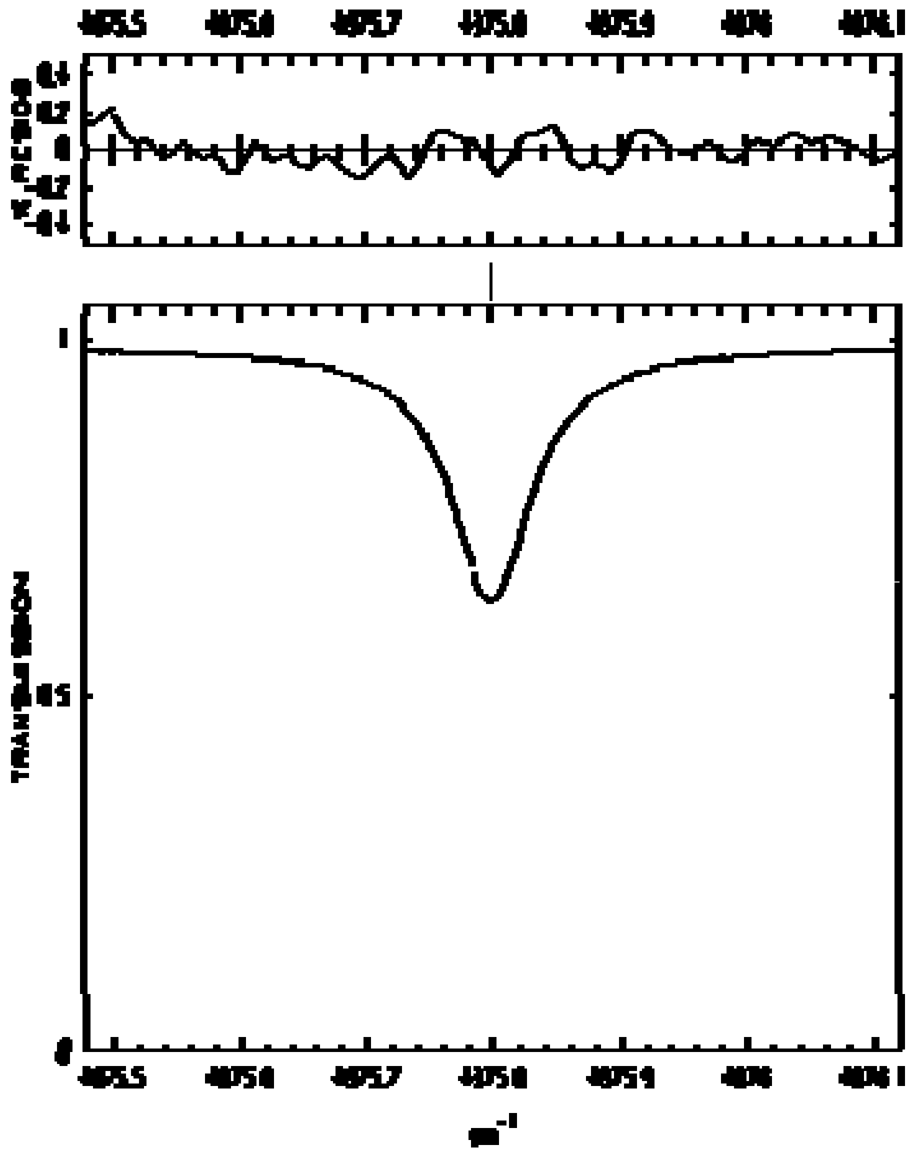
Difference between the PSU system and WLEF 76m CO_2 measurements in a test from April-August 2004. [Miles/Richardson/Uliasz, in prep.]

High Accuracy Analysis of R30 Intensity

Progress to date:

High accuracy determination of Voigt line shape parameters

- Line position
- Line strength
- Pressure-dependent shift and width (self-induced)



Bottom Panel: Short scan of the CO_2 spectrum centered on R(30) [20013 ← 00001] with the experimental conditions as follows: sample pressure of 269.03 Torr, optical path of 0.347 m and sample temperature of 297.04K.

Top Panel: Residuals from simulating the experimental spectrum. Note that the residuals are on the order of 0.2%, a factor of 10 smaller than required, although there are some small systematic residuals around the line center characteristic of non-Voigt line shape behavior.

New R(30) Spectral Parameters

Line	Position	Strength	o-c(%)	σ(%)	b0	Δb0(%)	d0	Δd0(%)
R30	4875.74873	1.50E-22	0.06	0.34	0.0897	2.2	-7.16	1.8

Computed and observed minus computed, (o-c)%, line strengths of $^{12}C^{16}O_2$ in cm^{-1}/(molecule cm^{-2}) at 296 K and standard mixture (0.9842 $^{12}C^{16}O_2$). σ(%) given relative to the strength value of Regalia-Jarlot et al. (2006).

Measured self-broadened $^{12}C^{16}O_2$ width coefficients b^0 with experimental width uncertainties, Δb^0 (in percent). Self-broadened half widths (HWHM) in units of cm^{-1}/atm at 296 K are in natural abundance (0.9842 $^{12}C^{16}O_2$).

Measured self-induced $^{12}C^{16}O_2$ shift coefficients, d^0 with shift coefficient uncertainties, Δd^0 (in percent). Self-induced pressure shift coefficients are in units of cm^{-1}/atm x 10^3 at 296 K for natural abundance (0.9842 $^{12}C^{16}O_2$).

Data from R. A. Toth, L. R. Brown, C. E. Miller
V. Malathy Devi, and D. C. Benner, *J. Mol. Spectrosc.*, in press (2006)

Conclusions

- System will operate at a temperature insensitive CO_2 line (2050.967 nm) with side-line tuning and off-set locking.
- Demonstrated an order of magnitude improvement in laser line locking needed for high precision measurements, side-line operation, and simultaneously double pulsing and line locking.
- Detector testing of phototransistor has demonstrated sensitivity to aerosol features over long distances in the atmosphere and resolve features ~ 100m.
- Optical systems that collect light onto small area detectors work well.
- Receiver optical designs are being optimized and data acquisition systems developed.
- CO_2 line parameter characterization in progress
- In situ sensor calibration in progress for validation of DIAL CO_2 system

Lidar parameters of a direct detection CO_2 DIAL with Phototransistor and large 16” telescope

Baseline DIAL system parameters

Pulse energy = 80 mJ single pulsed; 40/30 mJ double pulsed
Pulse width = 180 ns
Pulse repetition rate = 5 Hz
Spectrum = single frequency
On-line wavelength = 2050.967 nm
off-line wavelength = 2050.940 nm
Beam quality < 1.3 time diffraction limit
Long term (one hour) wavelength stability < 2 MHz
Wavelength accuracy < 0.5 MHz
Detector AlGaAsSb/InGaAsSb phototransistor
Quantum efficiency = 70%
Optical efficiency 60%
NEP = 5.0E-14 W/sqrt(Hz)
Telescope aperture = 16 inches
A receiver system with two detectors to collect near- and far- field signals is planned—the collected signal is split in the ratio 9:1 between the near and far field detector channels

Error Budget

Random error from signal shot noise and detector noise	0.5%
Systematic errors:	
CO_2 line temperature sensitivity	0.2%
CO_2 cross-section error (residual)	0.2%
Detector influence (uncompensated)	0.2%
Atmospheric number density error	0.05%
H_2O estimated dry air error	0.05%
Laser spectral error	0.05%
Total error (rms)	0.61%